Delta excitation in antiproton-deutron annihilation [*]

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Abstract

The Δ-excitation in $\overline{p}d$ annihilation at rest was studied. The annihilation amplitude from the statistical model and the πN amplitude from the resonance model were adopted in our calculations. We analyze the invariant mass of the $\pi^+ p$ and $\pi^- p$ systems selecting the protons with momenta above 400 MeV/c and with respect to the different final reaction channels. Our model reproduces reasonably the experimental data.

1 Introduction

One of the unique features of the annihilation of stopped antiprotons in nuclei is the production of very fast moving baryons. It was suggested by Armenteros and French [1] that the high momentum tail of the proton spectra in antiproton annihilation may be ascribed to the annihilation involving more than one nucleon. As was found by Hernandes and Oset [2] that a sizable increase of the fast moving nucleons are produced by the many-body annihilation mechanism. Furthermore, Cugnon et al. [3] suggested that the production of fast moving strange baryons implies the two-body annihilation mechanism.

However, a quite different mechanism of fast protons formation was suggested by Kudryavtsev and Tarasov [4].They suggest that the fast protons are produced in antiproton-deuteron annihilations due to pion absorption on the recoiling nucleon. Moreover the protons with very high momenta may be produced from the absorption and the emission of a meson by a baryon resonance.

One of the traditional mechanisms of fast baryon production following the antiproton annihilation is the secondary interactions of the pions as well as the mesonic resonances in the nuclear environment. It was shown by Sibirtsev [5] that the high momentum tail of the proton spectra from carbon and uranium targets can be reproduced with the rescattering and absorption of the annihilation mesons. Fasano

et al. [6] found that the pion rescattering can explain the fast proton production in the reaction $\overline{p}d \rightarrow 5\pi p$ but strongly underestimates the proton spectrum from reaction $\overline{p}d \rightarrow 3\pi p$.

It is clear that an essential indication for the contribution of the meson rescattering is the excitation of the Δ-resonances. Obviously the direct experimental evidence of secondary interactions of the mesons produced from annihilation is the observation of the isobar structure in the effective mass of the πN-system.

The search for isobar was performed in $\overline{p}d$ annihilation by Kalogeropoulos et al. [7], but they found no Δ influence in πN-system. However as was later shown by Voronov and Kolybasov [8] analyzing the reaction $\overline{p}d \rightarrow 2\pi^+3\pi^-p$ that the structure of the isobar may be significantly smeared out due to the contribution from πN-pairs in which the pion does not undergo rescattering. Moreover it was suggested that the Δ-resonance can be observed only when the recoil nucleons are selected with momenta above 200 MeV/c.

Recently the OBELIX collaboration from CERN measured the annihilation of stopped antiprotons in a deutron target [9]. The invariant mass of protons with momenta larger than 400 MeV/c and π^+-mesons indicates a clean peak from Δ^{++}-resonances, whereas the Δ^0-resonance in the $\pi^- p$ system was not found. Presently the isobar production in antiproton-deuteron annihilation is measured with respect to the different final channels [10].

In the present paper we study the Δ-excitation in $\overline{p}d$ annihilation at rest. The dependence of the Δ^{++}-production on the pion multiplicity is analyzed and the invariant mass of the πN-system for the reaction channels are predicted.

2 The model

Similar to [11] we calculate the amplitude of the triangle diagram shown in fig.1 as

$$T = \frac{E_\pi + E_p}{2\pi(m - E_\pi)} \int \frac{T_1(\overline{p}N \rightarrow n\pi)T_2(\pi N)}{\mathbf{k}_1^2 - \mathbf{k}_2^2 + i\epsilon} \phi(\mathbf{k}_1 + \mathbf{Q}/2)d\mathbf{k}_1 \tag{1}$$

where T_1 is the amplitude of $\overline{p}N \rightarrow n\pi$ annihilation, E_π and E_p are the pion and the proton energies in the final state, $\mathbf{k}_1$ and $\mathbf{k}_2$ are the pion momenta before and after the interaction. Here m is the nucleon mass and $\mathbf{Q}$ is the deutron momentum. The deutron wave function $\phi(\mathbf{Q})$ for the Bonn potential [12] was adopted.

We use the annihilation probability from [13] as

$$|T_1(\overline{p}N \rightarrow n\pi)|^2 = G_f \frac{\lambda^{1/2}(s, m^2, m^2)}{2m^2} \frac{P_n}{I_n(s)} \tag{2}$$

where s is the squared invariant mass of $\overline{p}N$ system and λ is the Kälen function. Factor G_f stands for the charge configuration of the final system of n-pions and was calculated with the statistical approach as [14]

$$G_f = [n_+!n_-!n_0!]^{-1} \left[\sum_\beta (n_+!n_-!n_0!)_\beta^{-1} \right]^{-1} \tag{3}$$

where n_+, n_- and n_0 are the numbers of positive, negative and neutral π-mesons for a final charge system of $n = n_+ + n_- + n_0$ pions and the summation is performed

over all reaction channels allowed for a given $n\pi$ system. Let us note, that the more complicated expression for G_f suggested in [15] is quite similar to the statistical factor (3).

In eq.(2) the factor $I_n(s)$ accounts for the phase space volume of n-pions with invariant mass $\sqrt{s}$ and P_n stands for the probability for the creation of n-pions in $\overline{p}N$ annihilation, which was taken as [16]

$$P_n = (2\pi\sigma)^{1/2} \, exp \left[-\frac{(n-\nu)^2}{2\sigma} \right]$$
$$\nu = 2.65 + 1.78 lns, \quad \sigma = 0.174\nu s^{0.2} \tag{4}$$

which are different from $\nu = 5.05$ and $\sigma = 0.76$ suggested in [15] for the annihilation at rest, but as we studied [17] do not change the results noticably.

Accordingly to Hernandez et al. [13] the annihilation amplitude has a smooth momentum dependence and the momentum distribution of the pions are described by the n-body phase space.

The $T_2(\pi N)$ amplitude accounts for the $\pi N \rightarrow \pi N$ scattering in the Δ-isobar region and was calculated with the resonance model [18, 19]. The cut-off parameter Λ was fitted to the experimental data of the total cross section for the $\pi^+ p$ interaction [20] (see fig.2). The lines show our calculations with the resonance model and the parameters Λ=0.3 GeV solid, 0.35 GeV dashed, 0.4 GeV dotted and 0.5 GeV dashed-dotted line. In the futher calculations we use Λ=0.33 GeV.

With fig.3 we demonstrate how reasonable the resonance model reproduces the angular spectra of the π-mesons. Here the dots show the experimental data on the differential cross sections of the reaction $\pi^+ p \rightarrow \pi^+ p$ plotted as a function of the $cos\theta$ in the c.m.s. system. The squares show the results for $s = 1.251$ GeV^2 [21], the triangles for 1.474 [22] and the circles for 1.711 [23] . The solid, dashed and dotted lines show our results calculated with the resonance model. The dashed-dotted line shows the function

$$\frac{d\sigma}{d\Omega} \propto 1 + 3cos^2\theta \tag{5}$$

which is valid in the central Δ-resonance region. Our results obtained with the resonance model are also in reasonable agreement with the Legendre expansions of the differential cross sections calculated from the Karlsruhe-Helsinki partial wave solution.

3   Results

The invariant mass distribution of the $\pi^+ p$ system produced in the annihilation of antiprotons on the deuteron at rest in the reaction $\overline{p}d \rightarrow p\pi^+ 2\pi^- m\pi^0$ are shown in Fig.4. The experimental data were taken from [9]. Similar as in ref. [9] we select the protons with momenta above 400 MeV/c. The dashed line shows the Δ^{++}-resonance, whereas the dotted line shows the combinatorial backround that comes from the pions which do not undergo interactions. The solid line is the sum and describes reasonably the experimental data. Note that the isobar resonance is slightly shifted to a higher mass in our calculations, which is due to the selection of the fast protons with momenta above 400 MeV/c. Surprisingly this obvious feature

was not observed in the experimental study [9]. The isobar structure is very clearly detected and reconstructed from the total invariant mass spectrum.

In fig.5 we show the contribution from the isobar (a) and the bakground (b) calculated for the reaction $\overline{p}d \rightarrow p\pi^+2\pi^-m\pi^0$ for $m = 0$ dotted, for $m = 1$ dashed, for $m = 2$ solid and for $m = 3$ dashed-dotted line. It is clear that the dominant contribution comes from the reaction channels with one and two neutral pions in the final state. The contribution to the Δ-excitation in the reaction $\overline{p}d \rightarrow p\pi^+2\pi^-$ is negligible, because the pions created in the annihilation have momenta which lead with a nucleon the excitations above the Δ resonance region.

A quite different situation exists for the π^-p invariant mass spectrum from the reaction $\overline{p}d \rightarrow p\pi^+2\pi^-m\pi^0$, which is shown in Fig.6. The signal from the Δ^0 resonance is to weak to be extracted from strong combinatorial background.

With our model we can also predict the isobar structure in the reaction channels which are now under study at CERN. Fig.7a shows the π^+p invariant mass spectrum from the reaction $\overline{p}d \rightarrow p2\pi^+3\pi^-$. Again we select protons with momenta above 400 MeV/c. Although the contribution from Δ^{++} is strong, it might be a difficult problem to extract it from the total spectrum, shown as the solid line. In fig.7b we show the π^+p invariant mass spectrum from the reaction $\overline{p}d \rightarrow p2\pi^+3\pi^-\pi^0$. The isobar structure can be clearly seen.

4   Conclusion

The Δ-excitation in $\overline{p}d$ annihilation at rest was studied. We use the annihilation amplitude from the statistical model [13]. The πN amplitude was calculated with the resonance model accounting only for the $\Delta(1232)$ resonance. We calculate the invariant mass of the π^+p and π^-p systems selecting the fast protons with momenta above 400 MeV/c.

We reasonably reproduce the new experimental data from the OBELIX collaboration at CERN. We found that the Δ^0 structure can not be observed in the π^-p invariant mass spectrum because of the strong contribution from the combinatorial background, in which the pions do not undergo an interaction.

Most promising is to study the Δ^{++} excitation in the reactions $\overline{p}d \rightarrow p\pi^+2\pi^-\pi^0$ and $\overline{p}d \rightarrow p\pi^+2\pi^-2\pi^0$. We also predicted that the observation of the Δ^{++} resonance in the reaction $\overline{p}d \rightarrow p2\pi^+3\pi^-\pi^0$ is significantly easier than with the reaction $\overline{p}d \rightarrow p2\pi^+3\pi^-$.

References

[1] Armenteros, R., French, B.: High Energy Physics, ed. E.H.S.Burhop, vol. 4, Academic Press, New Yourk (1969) 237.

[2] Hernandez, E., Oset, E.: Nucl. Phys. **A 493**, 453 (1989)

[3] Cugnon, J., Deneye, P., Vandermeulen J.: Phys. Rev. **C 41**, 1701 (1990)

[4] Kudryavtsev, A.E., Tarasov, V.E.: Sov. J. Nucl. Phys. **55**, 535 (1992)

[5] Sibirtsev, A.: Z. Phys. **A 345**, 59 (1993)

[6] Fasano, C.G., Locher, M.P., Nozawa, S.: Z. Phys. **A 338**, 95 (1991)

[7] Kalogeropoulos, T.E., Gray, L., Nandy, A., Roy, J.: Phys. Rev. **D 24**, 1759 ( )

[8] Voronov, D.V., Kolybasov, V.M.: JETP Lett. **57**, 163 (1993)

[9] Ableev, V.G., Agnello, M., Balestra, F., Bendiscioli, G., Bertin, A. et al.: Nucl. Phys. **A 585**, 577 (1995)

[10] OBELIX Collaboration, private communication.

[11] Kolybasov, V.M., Shapiro, I.S., Sokolskikh, Yu.N.: Phys. Lett. **B 222**, 135 (1989)

[12] Machleidt, R., Holinde, K., Elster, C.: Phys. Rep. **149**, 1 (1987)

[13] Hernandez, E., Oset, E., Weise, W.; Z. Phys. **A351**, 99 (1995)

[14] Pais, A.: Ann. Phys. (NY) **9**, 548 (1960)

[15] Iljinov, A.S., Nazaruk, V.J., Chigrinov, S.E.: Nucl. Phys. **A 382**, 378 (1982)

[16] Stenbacka, R., Walck, Ch., Ekspong, G., Nilsson, S., Gregory, P., Mason, P., Muirhead, H., Warren, G.: Nuovo Cim. **A 51**, 63 (1979)

[17] Sibirtsev, A.: Sov. J. Nucl. Phys. **55**, 541 (1992)

[18] Tsushima, K., Huang, S.W., Amand Faessler: Phys. Lett. **B337**, 245 (1994)

[19] Tsushima, K., Huang, S.W., Amand Faessler: J. Phys. **G21**, 33 (1995)

[20] Landolt-Börstein: New series, vol.I/12, ed. H.Schopper (1988)

[21] Auld, E.G. : Can. J. Phys. **57**, 73 (1979)

[22] Bussey, P.J., Carter, J.R., Dance, D.R., Bugg, D.V., Carter, A.A., Smith, A.M.: Nucl. Phys. **B 58**, 363 (1973)

[23] Gordeev, V.A., Koptev, V.P., Kruglov, S.P., Kuzmin, L.A., Kubardis, A.A., Malov, Yu.A., Strakovskii, I.I., Shcherbakov, G.V.: Sov. J. Nucl. Phys. **24**, 599 (1976)

Figure captions

Figure 1: Pion rescattering diagram.

Figure 2: The total π^+p cross section. Experimental data are from [20]. Lines show our calculations with cut-off parameters: 0.3 -solid, 0.35-dashed, 0.4-dotted and 0.5 GeV- dashed-dotted.

Figure 3: The angular spectra of pions from the reaction $\pi^+p \to \pi^+p$ in the c.m.s. system. Experimental data are from [21, 22, 23] for $s = 1.251$ GeV^2 -squares, 1.474-triangles and 1.711-circles. The solid, dashed and dotted lines show our results calculated with the resonance model. The dashed-dotted line shows (5).

Figure 4: The invariant mass spectrum of the π^+p system in the reaction $\overline{p}d \to p\pi^+2\pi^-m\pi^0$ for protons with momenta above 400 MeV/c. Experimental data are from [9] and lines show our results. Dashed line shows the contributon from Δ^{++}-excitation and dotted from the bakground. Solid is the sum.

Figure 5: The invariant mass spectrum of the π^+p system in the reaction $\overline{p}d \to p\pi^+2\pi^-m\pi^0$ for protons with momenta above 400 MeV/c. Fig.a) shows the contributon from Δ^{++}-excitation and Fig.b) from the bakground. Dotted lines show the contribution from $m = 0$, dashed-$m = 1$, solid-$m = 2$ and dashed-dotted-$m = 3$.

Figure 6: The invariant mass spectrum of the π^-p system in the reaction $\overline{p}d \to p\pi^+2\pi^-m\pi^0$ for protons with momenta above 400 MeV/c. Experimental data are from [9] and lines show our results. Dashed line shows the contributon from Δ^0-excitation and dotted from the bakground. Solid is the sum.

Figure 7: The invariant mass spectrum of the π^+p system in the reaction $\overline{p}d \to p2\pi^+3\pi^-$ (a) and $\overline{p}d \to p2\pi^+3\pi^-\pi^0$ (b) for protons with momenta above 400 MeV/c. Dashed lines show the contributon from Δ^{++}-excitation and dotted from the bakground. Solid lines are the sum.